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Green energy at cement kiln in Cyprus—Use of sewage sludge as a conventional fuel substitute

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Abstract

In this paper, the results of a study concerning the utilization of sewage sludge as an alternative fuel at cement kilns, covering all process, health and safety and environmental matters, are presented. Trials have started in Vassiliko Cement Plant (Cyprus), on how to treat and utilize wet sewage sludge, of moisture content 65–70%, as an alternative fuel at the cement kilns of the plant. Environmental gaseous emission measurements, with emphasis on heavy metal concentrations, especially those of mercury (Hg), have been performed. At Vassiliko Plant, 22 000 m^3 of wet sludge has been treated during the years 2003 and 2004. The new technology involves mixing of sewage sludge with pet coke and then incinerating the mixture at high temperatures. Since cement plants burn fuel at 1400 °C, the new sewage sludge-based fuel does not emit dioxin harmful to human health.

Keywords: Sewage sludge; Fuel substitute; Cement kiln; Emissions; Heavy metals

Contents

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1. Introduction

One of the most interesting wastes, which can be utilized in an effective and environmentally friendly manner, is the sewage sludge coming from the treatment of municipal wastewaters. If utilized properly, sewage sludge creates very little to zero environmental impacts. Opinions on its utilization vary due to the fact that the various parties rise up their positive and/or negative points, as regards sludge handling and treatment. Sewage sludge is a renewable product that will never end. And its annual production will rise in the future. The main issue normally raised by the citizens, is that of its unpleasant odor; besides, the high content of moisture, heavy metals and other potential harmful substances makes utilization of sewage sludge one of the most difficult processes of environment protection.

There are different methods employed in treating of the sewage sludge. When referring to sewage sludge, we concentrate mainly on the solid cake produced after treating the incoming sewerage of the wastewater treatment plant [1,2]. The most abundant methods of utilization are those concerning use in agriculture, disposal in landfills or use as a conventional fuel substitute for energy production. The partly de-watered sewage sludge can be used, as already referred to, for agricultural purposes as a non-composted or as a composted matter. The non-composted matter is used as a conventional fertilizer replacing and improving the physical properties of the soil, but the addition to the land must be controlled with time. The variation of agricultural production with time is in contrast with the continuous sludge production. Nutrient addition to the soil is also associated with the addition of pollutants to it. The pollutants can enter plants, underground waters and the air through washing processes and microbiological conversion. Such matter is suitable for small sewage plant units without pollutants. The composted matter on the other hand is a stabilized product, which can be stored and used for agricultural reasons when needed. It is better stabilized in organic matter due to the addition of agricultural waste, which facilitates the composting process. As a result it improves the aeration, drainage and nutrient hold of the land. However, the storage of the material is a potential problem due to its unpleasant odor, which is most of the times present because of malfunctioning of the composting plants. The market of the final product compost is also limited and with the passage of time large quantities are accumulated. Chemical analyses and toxicity testing were employed [3], in conjunction to evaluate the environmental hazard from the wasted sludge generated during the biological treatment of urban and industrial wastewaters. Those chemical analyses included determination of seven polychlorinated biphenyls (PCBs), 13 polycyclic aromatic hydrocarbons (PAHs), total organic carbon (TOC) and seven heavy metals (As, Cd, Cr, Cu, Pb, Mn, and Zn) in sludge. The urban sludge was found to be more enriched with PAHs than the industrial sludge, however, at levels below the EU limits for sludge application. The urban sludge exhibited high ecotoxicity.

The results of the study revealed the necessity for combining chemical with ecotoxicological criteria for integrated characterization of wasted sludge and the need for harmonization of the methods employed for waste classification. Although the use of sludge as fertiliser presents potential resource and environmental advantages, it can have negative effects on people and soil productivity [3–8].

The sludge can also be disposed to landfills and in a lot of cases, where space and neighborhood conditions are favorable it is a good solution. Such an activity complies till nowadays with the legislation and is accepted by humanity. However, odor is a nuisance when the wind direction brings it to inhabited areas. The drainages created due to landfill disposal need treatment in case of unaccepted pollutant levels and unless the layer thickness of the sludge is not very low it does not dry out. The feasibility of using solidified sludge as a landfill cover material was considered in the context of the economical recycling of waste by Kim [9]. Sludge solidified using the CSS technology exhibited geotechnical properties that are appropriate for replacing currently used cover soil. Microscopic analyses using XRD, SEM and EDS revealed that the main hydrated product of solidification was CSH ($CaO \cdot SiO_2 \cdot nH_2O$), which may play an important role in the effective setting process [9].

The de-watered sludge can also be used as a fuel substitute for the production of energy. There are various methods of burning sludge and utilize the energy produced, but we will concentrate on its firing in the cement plant. Firing of sludge will eliminate it, whilst at the same time energy is produced. Therefore, all negative effects associated with its presence are removed and the environmental requirements are met. Also, reduction in energy demands and costs is observed [10,11].

Modern pyrolysis or gasification techniques [1,12–17] are attractive, but cost ineffective, whereas past techniques of disposal to the sea, are no more acceptable. The high content of moisture, heavy metals and other potential harmful substances makes utilization of sewage sludge one of the most difficult processes of environment protection. In many countries, coal is still the most popular fuel, used to provide hot water and heating for buildings. On the contrary, co-combustion of sludge with coal in stoker-fired boilers is applicable. There are two significant points: ecological and exploitation requirements. The important restriction of the sludge/coal ratio is the emission of harmful substances with heavy metals and dust. Their concentrations in the flue gas should meet the environmental regulations. The other factor influencing the co-combustion process is the change of physical and thermal properties of the fuel: heating value, moisture content and ash composition. These influence the thermal output of the boiler, the amount of air required for combustion, the volume of the flue gases and dust concentration and particle distribution. Experimental studies have shown that increase of the sludge ratio in the fuel have resulted to increase of nitric oxides and sulfur oxides [15]. Since removal of these components from flue gas needs expensive installations, the ratio of sludge in the fuel must be controlled carefully.

As mentioned earlier the most common sewage sludge disposal alternative is incineration and deposition in controlled landfills. However, space limitations on existing landfill sites and increasing environmental concerns have prompted the investigation of alternative ash disposal routes.

Another important issue that has been prompted is the disposal of ash. Sewage sludge ash has been used to manufacture bricks, to incorporate into concrete mixtures and as a fine aggregate in mortar. Researchers [30] have studied the thermal co-process of municipal solid waste (MSW) and other raw materials needed for the production of clinker and

consequently mortar, without causing environmental problems. The technique used was related to a method of manufacturing mortar by firing a mixture of mineral raw materials (limestone, clay, silica and iron oxide) together with dried and properly treated solid waste, at high temperature (850–1100 °C). The heavy fraction of the dried and crushed solid waste is introduced at the 850–1100 °C zone of a two stages rotary kiln. The light fraction is used with a mixture of pet-coke, in an appropriately designed jet burner in order to heat the rotary kiln. The clinker obtained is milled together with gypsum to produce a hydraulic mortar for building applications. The main advantages of the method were the significant volume reduction of MSWs by incineration without toxic gas emissions and the production of a valuable material. The following economic analysis carried out by Sikalidis [30], concluded that the installation of a unit, with a MSW capacity of 500 t/d, producing about 433 t/d of mortar, seemed to be economically profitable. Several other works have been carried out in this field [18–22]. In the light of the results from these works it was concluded that the main objective of using treatment plant sludge as an additional component in a construction material, Portland cement concrete, is possible. The most important physical and mechanical properties of concrete-containing treatment plant sludge were evaluated. Nevertheless, other characteristics, such as the origin of the sludge, the materials used, the compatibility of the sludge within the cement matrix and the production of specimens should be taken into account.

An enormous effort has been made recently in the cement-manufacturing industry to replace the conventional fuels with alternative ones. In order to reduce the energy demands/costs and meet the environmental requirements, Kääntee et al. [11] used a commercial tool (ASPEN PLUS) to evaluate different scenarios of fuel being used in the process. The goal was to optimize process control and alternative fuel consumption, while maintaining product quality. The aim of using the model was to describe the behavior of the kiln process when the fuel is fully or partly replaced by an alternative fuel. The reference case of the model was the use of pet coke as the only primary and secondary fuel, while different other scenarios with alternative fuels, replacing partly the primary or secondary fuel, were assessed. The investigated scenarios referred to meat and bone meal and sewage sludge used as alternative fuels. The calculations have shown that for alternative fuels like bone meal and sewage sludge, the air quantity needed is slightly higher (3–4%). In addition, the need for combustion air is about 2% less than in the reference case, while the energy inputs are 20 kcal/kg lower than for the reference case. All in all, Kääntee et al. [11] suggest that as a rule of thumb, the maximal sewage sludge feed rate should not be more than 5% of the clinker production capacity of the cement plant. Consequently, for a 2000 t/d cement kiln, a maximum of a 100 t/d dry sludge might be used. Many studies have been conducted on emissions from sludge and on synthesis and destruction of PCDD and PCDF inside a MSW incinerator and combustor [18,23–25] and practical concepts to minimize the emission of halogenated organic compounds from MSW incinerators have been published [26].

In terms of emissions, the suspended fine limestone particles are effective in the removal of acidic gaseous pollutants from sludge combustion. The heavy metals from sludge are adsorbed on the particles and returned into the kiln after separation in the E-filter. However, one may expect clogging of the cyclone pre-warmer if the sludge has more than 0.2–0.5% Cl. If sewage sludge is intended to be co-fired in cement works, then lime stabilization may be recommended. It has been shown that the ash from lime stabilized and

conditioned sludge, normally 0.3–0.5 kg CaO/kg dry sludge, has compositions closer to those of cements.

Any sludge treatment should be directed towards reduction of its odor, reduction of organic solids, minimization of pathogens, improving de-watering characteristics and reduction of moisture content [10,27,31]. All these are governed by legislation since the waste sludge should be treated in such a way so as to ensure proper fledgling, environmental protection of water, soil and air and, finally, technical convertibility. To assure the above demands, it is essential to ensure good stabilization and de-watering of the sludge through one or more of the following stages:

(a) Digestion (aerobic or anaerobic).
(b) Lime addition on raw sludge.
(c) Thermal treatment 30–75 °C and 75–90 °C.
(d) Composting.
(e) De-watering (centrifuge, filter press, vacuum filters etc).
(f) Drying if required, but this needs energy.

The final de-watered product is the product that the cement industry or the energy producer is focusing on.

The purpose of the present study was the investigation of the utilization of wet sewage sludge of moisture content 65–70%, as alternative fuel at cement kiln, covering all process, health and safety and environmental matters, by contacting trials on full-scale basis, in Vassiliko Cement Plant in Cyprus. The ultimate aim is the elimination of sludge supplied by two major cities of the island, with parallel fuel saving in the cement production kiln. Firing sludge in the cement kiln is done through co-incineration. In other words the sludge is fired together with conventional fuel. This is perhaps the best approach when the sludge cannot be utilized safely elsewhere.

2. Sewage sludge use as alternative fuel in cement plant in Cyprus

The cement industry can utilize a lot of other alternative fuels as substitutes to conventional fuel with substantial subsidies in a lot of cases. The cement industry, therefore, does not seek anxiously to utilize sewage sludge if somebody else wants it. However, being environmentally committed Vassiliko Plant is willing to help in solving the problems associated with the storage and/or accumulation of sludge, provided that the producer (treatment plant management) of the sludge is willing to at least pay for its handling costs.

Trials have started in Vassiliko cement plant on how to treat and utilize wet sewage sludge of moisture content 65–70%, as an alternative fuel at the cement kilns of the plant. Environmental gaseous emission measurements, with emphasis on heavy metal concentrations, especially those of mercury (Hg), have been performed. The process methodology is well established. The new technology involves mixing sewage sludge with used pet coke and then incinerating the mixture at high temperatures (1400 °C).

3. Characteristics of sewage sludge in Cyprus

The traditional fuels used in the cement manufacturing process are gas, oil or coal, whilst the alternative ones can be materials like waste oils, plastics, auto residues, waste

tires and sewage sludge. In order to use these fuels in a cement factory, the composition of the fuel must be precisely known. The choice, as to which fuel will be finally used, is based upon several criteria, i.e. the price and the availability, the energy and ash contents, the moisture and volatiles contents. Table 1 reports alternative fuel for the cement industry grouped into three categories and Table 2 depicts various characteristics of sludge from Cyprus of varying dry solids content. It can be observed that the calorific value for high volatile solids content dry sludge is quite high, whereas for low volatile solids content this drops drastically. The question therefore, arises as to what volatile solids levels of treatment have to be reached. This is of outmost importance especially if the sludge will be utilized for energy production.

4. Moisture content of sludge from Limassol and Larnaca districts

We referred so far to firing de-watered sewage sludge, but in reality the producer's main problem is how to dry effectively the material. A filter press can only produce sludge with 70–75% moisture under the best conditions. Sun or open air-drying is normally the

Table 1
Alternative fuel options for the cement industry [32]

Liquid waste fuels	Tar, chemical wastes, distillation residues, waste solvents, used oils, wax suspensions, petrochemical waste, asphalt slurry, paint waste, oil sludge
Solid waste fuels	Pet coke, paper waste, rubber residues, pulp sludge, used tires, battery cases, plastic residues, wood waste, domestic refuse, rice chaff, refuse derived fuel, nut shells, oil-bearing soils, sewage sludge
Gaseous waste	Landfill gas, pyrolysis gas

Table 2
Characteristics of sludge of varying dry solids content

Sludge category	A	B1	B2	C	D
Dry solids (kg/m^3)	12	9	7	10	30
Volatile solids (%), dry basis	65	67	77	72	50
pH	6	7	7	6.5	7
C	51.5	52.5	53	51	49
N	4.5	7.5	6.3	7.1	6.2
C/N	11.4	7.0	8.7	7.2	7.9
P	2	2	2	2	2
Cl	0.8	0.8	0.8	0.8	0.8
K	0.3	0.3	0.3	0.3	0.3
Al	0.2	0.2	0.2	0.2	0.2
Ca	10	10	10	10	10
Fe	2	2	2	2	2
Fats	18	8	10	14	10
Proteins	24	36	34	30	18
Low calorific value (cal/g)	4200	4100	4800	4600	3000

method used to reduce further the sludge moisture. This is achievable only if the sludge layer is very low. To succeed in this huge areas of land are required and normally this is not feasible. So, the producer ends up with a product that is laid in high layer resulting in inefficient drying.

It is important to avoid carbonization of the sludge during drying, since at carbonization temperature (160 °C) the mercury emissions are at the highest level. To avoid reaching this carbonization temperature, lime can be added to the sludge. This raises the carbonization temperature and so at 150–160 °C the Hg evaporation is very low. In the cement kiln the sludge fuel meets too high levels of CaO and this avoids rapid Hg evaporation. With the presence of minute amounts of copper in the kiln the Hg is trapped as an amalgam. In the cement plant before firing the sludge must be dried to 1% moisture. Normally, the sludge can be dried with some lime present (to raise the carbonization temperature) at $T = 180–200\,^{\circ}C$. Drying of the sludge with hot gases should be performed in an inert atmosphere (hot air with $O_2 > 16\%$ can cause ignition).

At Vassiliko sludge is received with a moisture content of 65–70% and to avoid its nuisance odor, it is mixed immediately with raw conventional solid pet-coke and at the same time its moisture in the mixture is reduced. It is then fed for drying and grinding to the coal mill. Drying is achieved using cooler hot air at 250 °C maximum and so no fuel costs are required for drying. The danger of ignition is very remote since the mixture has a lot of pet-coke of low volatiles content. Mixing is performed in a properly designed effective mixing drum. At Vassiliko Plant 22 000 m^3 of wet sludge has been treated during 2003–04. The method used could be the solution for other districts in Greece, such as Psitalia (Athens district). The 4.5 million inhabitants and industries of the Attica Basin used to offload an impressive 800 000 m^3 of waste into Saronic Gulf every day. Today, the Biological Waste Treatment Plant of Psitalia, one of the largest waste treatment centers in Europe, contributes decisively to cleaning up the gulf. But, still no treatment of the produced sewage sludge takes place; this result to sludge's transport abroad (Germany). The construction of the drying unit is expected to finish until spring of 2007. According to the method, the material must be transported to the various cement plants for treatment and firing at a good subsidy as an incentive to the cement industry's manager to destroy the sludge. The savings, out of using a 7.5% wet sludge in 1 kiln normally consuming 6.3 t/h dry pet-coke (1% moisture), reach 8.0 €/h.

5. Heavy metals in sewage sludge from Limassol and Larnaca districts

The concentration of heavy metals in the sewage sludge is a governing factor for its disposal either at landfill or for agricultural purposes. The European Union and subsequently each member state have legislative rules as to the amount of heavy metal that the ground can accommodate [10,27,31]. Table 3 shows the concentration (mg/kg) of heavy metals in the sludge produced from the treatment of the sewerage's of Limassol and Larnaca districts and the corresponding acceptable limits for each metal.

The high sludge volatile matter enforces a better pet coke ignition and any ash residue that is produced is embodied in the kiln's clinker product (heavy metals are present there). The ash constituents are similar to those of clinker produced without sludge firing and the ash serves as a 28-day strength improver of cement.

Table 3
Sludge produced in sewerage's of Limassol and Larnaca districts

H.M	Limassol (mg/kg)	Larnaca (mg/kg)	Limit (mg/kg)
Cu	4.5	27.5–139.0	1000–1750
Fe	35813.0	15 000–30 000	No problem
Cr	31.7	3.8–24.8	—
Cd	1.4	1.0–1.6	20–40
Ni	35.9	25.8–120	300–400
Pb	18.8	24.5	750–1200
Zn	2640.0	804.4	2500–4000
Hg	0.4	0.65	16–25

6. Emissions measurements at Vassiliko plant

When fired–combusted, the gaseous emissions can be monitored accurately in real time and continuously [11]. The input fuel sludge can be analyzed frequently for its properties. The high cement kiln temperature (1450 °C) and the rapid cooling of gases hinders the formation of dioxins/furans, whereas any heavy metals present in the sludge are frapped in the liquid fraction of the raw materials at the kiln's sintering zone. Being a biomass fuel it helps the cement plant reduce its CO_2 conventional fuel emissions as well as the country's and global in general CO_2 emissions. Using it as a substitute fuel helps in saving reserves of conventional fuels and is accepted as a renewable fuel energy source. It is a fact that its life cycle is much smaller to any other disposal method.

It has been observed that the alkaline kiln environment removes any traces of HCl and/or HF produced during firing and the low primary air used in third-generation burners creating a low-flame temperature hinders the thermal conversion of sludge nitrogen to NO_x [28]. Last but not least, the use of sludge as a substitute fuel results in reducing the export currency required for conventional fuels. If, however, the levels of mercury (Hg) and thallium (Tl) are high, a good monitoring of those volatile heavy metals should be established. To avoid such a possibility although the mercury level in the sludge fuel can reach 16 mg/kg the cement industry aims to fire sludge with a maximum mercury content of 0.5 mg/kg [29].

The mercury concentrations in the fuel gases are of outmost importance in EU and everyone should conform to the legislative requirements imposed. Normally mercury in the sludge comes from either the cleaning process at the sewage plant and/or from the incoming sewerage where it is present. Naturally, mercury concentration worldwide is arising from human activities and from metal treatment, waste incineration (batteries), chlorine production, fossil fuel burning, crematories and dentistry. The world total mercury amounts reach 30 000 t/annum. Cement industry co-incineration of wastes is considered as an acceptable option further and further by the decision-makers in the EU. In the absence of other environmentally acceptable techniques it is also considered as recycling of matter [27]. Bearing in mind that the gaseous emissions can be continuously monitored in real-time, everyone can be aware of any dangers that may arise.

The results of the gaseous emissions from Vassiliko Plant, as measured by independent laboratory are depicted in Table 4. As it can be seen, gaseous heavy metal concentrations amount to only 16% of the allowable levels and dioxin/furans amount to only 6% of the

Table 4
Results of the gaseous emissions

Metal	mg/Nm^3	Dioxin/furans	Ng/Nm^3
Cd	0.0008	TCDD	0.0016
Tl	0.0050	PeCDD	0.0016
Hg	0.0014	HxCDD1	0.0002
As	0.1221	HxCDD2	0.0001
Co	0.0034	HxCDD3	0.0002
Ni	0.0945	HpCDD	0.0001
Se	0	OCCD	0.0001
Te	0	TCDF	0.0009
Sb	0	PeCDF1	0.0001
Cr	0.0795	PeCDF2	0.0012

allowable levels. The allowable concentrations according to the legislation are as following: most important is the total concentration of heavy metals, which cannot exceed 5 mg/Nm^3 (5000 μg/Nm^3). This has to be the sum of the three classes of heavy metals assigned by the EU legislation (European Commission, 2001) [27] such as:

(a) *Class* I. Cd, Hg, Tl, with maximum limit of 0.2 mg/Nm^3 (200 μg/Nm^3). In the present study the results are $\Sigma(0.0008 + 0.005 + 0.0014) = 0.0072$ mg/Nm^3.
(b) *Class* II. As, Co, Ni, Se, Te with maximum limit of 1.0 mg/Nm^3 (1000 μg/Nm^3). In the present study the results are $\Sigma(0.1221 + 0.0034 + 0.0945 + 0 + 0) + 0.2200$ mg/Nm^3.
(c) *Class* III. Sb, Pb, Cr, Cu, Mn, Sn, V with maximum limit of 5.0 mg/Nm^3 (5000 μg/Nm^3). In the present study the result is $\Sigma(0 + 0.1757 + 0.0795 + 0.0241 + 0.1161 + 0.1704 + 0.0030) = 0.5688$ mg/Nm^3.

This makes a total of 0.7960 mg/Nm^3 versus allowable of 5.0 mg/Nm^3. As far as dioxin/furans are concerned, the allowable concentrations cannot exceed the 0.1 ng/Nm^3. This has to be the sum of all the 17 types of dioxin/furans. The result of this study is only 0.006 ng/Nm^3.

7. Conclusions

Co-incineration processing of sewage sludge in cement factory of Vassiliko plant in Cyprus is the alternative to other ways of utilization of sewage sludge from Limassol and Larnaca districts. In this way one unlikely source—municipal sewage sludge—may hold a key to providing a reliable, low-cost source of energy, while helping to make the most abundant supply of energy, coal, and last even longer. The net environmental benefit is that unused wastes, traditionally considered an environmental problem, can be processed into renewable fuel that not only produces energy, but reduces carbon dioxide emissions as well. The material must be transported to the various cement plants for treatment and firing at a good subsidy as an incentive to the cement industry's manager to destroy the sludge. Heavy metal concentrations in gas amount to only 16% of the allowable levels and dioxin/furans amount to only 6% of the allowable levels. The saving out of using a 7.5% wet sludge in one kiln normally consuming 6.3 t/h dry pet-coke (1% moisture) reach

8.0 €/h. The methodology used can be applied in any cement plant and it seems to be the only solution to solve Psitalia's (Athens larger district) sludge problem also.

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